

The 17 min orbital period in the Ultra Compact X-ray Binary 4U 0513-40

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ABSTRACT

The ultracompact low-mass X-ray binary 4U 0513–40 in the globular cluster NGC1851 exhibits large amplitude X-ray flux variations with spectral changes from low/hard to high/soft states which have not been reported previously in other ultracompact X-ray binaries. Using *BeppoSAX*, *Chandra* and *XMM-Newton* archival data together with recent *INTEGRAL* observations, we reveal a clear sinusoidal periodic signal with a period of ~ 17 minutes when the source is in a typical high/soft state with a dominant soft thermal component. The periodicity disappears when the source is in a low/hard state and the thermal soft component is not required any more to model the data. These properties indicate the orbital nature of the detected signal and imply an high inclination angle of the binary system ($> 80^\circ$).

Key words: gamma-rays: observations X-rays: observations

1 INTRODUCTION

Ultracompact X-ray binaries (UCXBs) are systems with orbital periods (P_{orb}) shorter than ≈ 1 hr in which a neutron star or black hole accrete matter from a companion low mass star. Their short periods rule out ordinary hydrogen-rich companion stars, since these stars are too big and do not fit in the Roche lobe (Nelson et al. 1986). UCXBs are rare objects and their identification is very difficult because of the difficulty to measure P_{orb} in LMXBs. The most recent compilation of ultracompact X-ray binaries lists 27 candidates (in 't Zand et al., 2007). Eight out of 52 LMXBs with measured orbital period are in the ultracompact regime (in 't Zand et al. 2007, Nelemans & Jonker 2006). The remainder were classified as ultracompact X-ray binaries on the base of some combination of tentative orbital period measurements, deep optical spectra lacking hydrogen emission lines, high ratios of X-ray to optical flux, or persistent emission at low fractions of the Eddington rate (in 't Zand et al. 2007 and references within). The IBIS results of the long monitoring of the UCXBs showed that these sources spend most of the time in the canonical low/hard state, with X-ray luminosities $\lesssim 7 \times 10^{36} \text{ erg s}^{-1}$, plasma temperature $kTe \gtrsim 20 \text{ keV}$ and $\tau \lesssim 4 - 5$ (Fiocchi et al. 2008).

4U 0513-40 is an X-ray binary in the Galactic globular cluster NGC 1851 with a 17-minute orbital modulation first observed with the *Hubble Space Telescope* (Zurek et al. 2009). It is a persistent source showing evidence for variability of a factor of ~ 10 in X-ray luminosity on timescales of \sim weeks, and a factor of more than

20 overall (Maccarone et al. 2010). Such variability is unusual for ultracompact X-ray binaries and hence deserve some attention.

2 OBSERVATIONS AND DATA ANALYSIS

Table 1 gives a summary of source observations performed with instruments on board *BeppoSAX*, *Chandra*, *XMM-Newton* and *INTEGRAL* satellites.

The LECS, MECS and PDS/*BeppoSAX* event files and spectra were generated with the Supervised Standard Science Analysis (Fiore, Guainazzi & Grandi 1999). Both LECS and MECS spectra were accumulated in circular regions of $8'$ radius. Publicly available matrices were used for these instruments. The PDS spectra were extracted using the XAS version 2.1 package (Chiappetti & Dal Fiume 1997). The background sampling was performed by making use of the default rocking law of the two PDS collimators that sample ON/+OFF, ON/-OFF fields for each collimator with a dwell time of 96 s (Frontera et al. 1997). When one collimator is pointing ON-source, the other collimator is pointing toward one of the two OFF positions. We used the standard procedure to obtain PDS spectra (Dal Fiume et al. 1997). The *Chandra* data were processed with the CIAO (*Chandra* Interactive Analysis of Observations) software, version 4.1.2, i.e. the same version of CALDB (Calibration Data Base), provided by the *Chandra* X-ray Center and following the science threads listed on the CIAO website¹. The CIAO routine `wavdetect` was used to search for X-ray sources on

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¹ Available at <http://cxc.harvard.edu/ciao/>

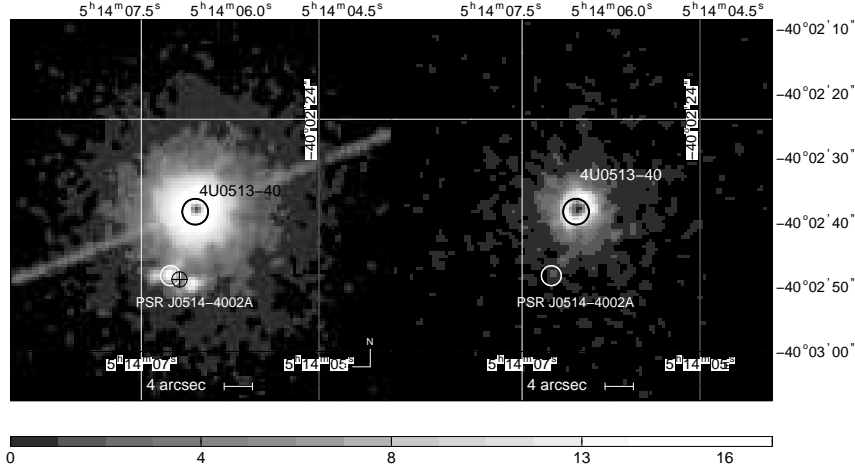


Figure 1. Left: ACIS 0.5–8 keV image of the region surrounding 4U 0513–40. A Gaussian smoothing was applied to the counts distribution with a width of 2 pixels. The black circle represent the detection of the X-ray source 4U 0513–40, the cross indicate the pulsar PSR J0514–4002A position and the white circle is the *Chandra* detection. Right: ACIS 4–8 keV image of the region surrounding 4U 0513–40. A Gaussian smoothing was applied to the counts distribution with a width of 2 pixels. The black circle represent the detection of the X-ray source 4U 0513–40.

the ACIS chips. The CIAO routine `dmextract` was used to produce energy spectra and `mkacisrmf` and `mkarf` for the response and ancillary files respectively. We extracted source photons from a circular region centered on the source with an extraction region of 8 arcsec. For the background, we used circular source-free regions in the same CCD of the studied source.

XMM-Newton data have been processed starting from the observation files with SAS 7.0.0. X-ray events corresponding to patterns 0–4 were selected from EPIC-pn camera. We used the most updated calibration files available at the time of the reduction for each source data. Source light curves and spectra were extracted from circular regions of 10'' centered on the source, while background products were obtained from off-set regions close to the source. The ancillary and detector response matrices were generated using the *XMM-Newton* SAS `arfgen` and `rmfgen` tasks.

The analyzed *INTEGRAL* (Winkler et al. 2003) data consist of all public observations in which 4U 0513–40 was within the field of view of the high-energy detectors. Broad-band spectra, ~ 5 –80 keV, are obtained using data from the high-energy instruments, JEM-X (Lund et al. 2003) and IBIS (Ubertini et al. 2003). The IBIS and JEM-X data have been processed using the Off-line Scientific Analysis (OSA v. 9.0) software released by the *INTEGRAL* Science Data Center (ISDC, Courvoisier et al. 2003). Light curves and spectra are extracted for each individual science windows. These runs were performed with AVES cluster, designed to optimize performances and disk storage for the *INTEGRAL* data analysis (Fed-erici et al. 2010).

3 IMAGE ANALYSIS

The excellent angular resolution provided by *Chandra* allows us to resolve the 4U 0513–40 X-ray emission from the binary Pulsar PRS J0514–4002. Figure 1 shows the 0.5–8.0 keV (left panel) and 4–8 keV ACIS image (right panel). The CIAO routine `wavdetect` was used to search for X-ray sources. This routine found two sources in the 0.5–8.0 keV: the first located at RA=05 14 06.48 and DEC=–40 02 38.8 with a positional uncertainty of 0.64 arcsec ($1-\sigma$ statistical errors) and the second at RA=05 14 06.79 and DEC=–40 02 48.5 with positional uncertainty of 1.3 arcsec ($1-\sigma$ statistical er-

Table 1. Summary of the X-ray binary 4U0513-40 observations

Instrument	Tstart MJD	Exposure ks
BeppoSAX/LECS	51597.6	31.5
BeppoSAX/MECS	51597.6	73.6
BeppoSAX/PDS	51597.6	34.9
XMM Newton/PN	52730.0	23.5
CHANDRA/ACIS	54560.6	18.8
INTEGRAL/JEM-X	53917.6	102.8
INTEGRAL/IBIS	53380.4	601.5

rors). Only UCXB 4U 0513–40 was detected in the 4–8 keV energy range (see Figure 1). Image analysis of the *Chandra* observation shows that only the ultra compact binary system is emitting at high energy and this suggest only 4U 0513–40 as the only possible counterpart of the very high energy (*BeppoSAX* and *INTEGRAL*) object. In fact the Pulsar source is too weak to be the counterparts of the IBIS and PDS source. This is in line with the peculiar nature of this binary Pulsar, being a radio steep and very faint pulsar (Freire et al. 2007).

4 TEMPORAL ANALYSIS

We accumulated a 16s bin light curve in the 0.3–5 keV energy band, using the ACIS/*Chandra* data and calculated a power spectrum over the whole observation following the method outlined by Israel & Stella (1996). The power spectrum is shown in Figure 2 (top panel) where a peak at 0.00099 Hz is clearly observed. The 4U 0513–40 period was obtained with an epoch-folding technique. The best-fit period is (1004 ± 18) s with uncertainties at 1σ confidence level. Using this period value, we folded the light curves and a sinusoidal shape of the modulation was found (see Figure 2, bottom panel) with a pulsed fraction of $\sim 11\%$ (i.e. the semi amplitude of the modulation divided by the mean source count rate).

During the *BeppoSAX* observation, a type-I thermonuclear

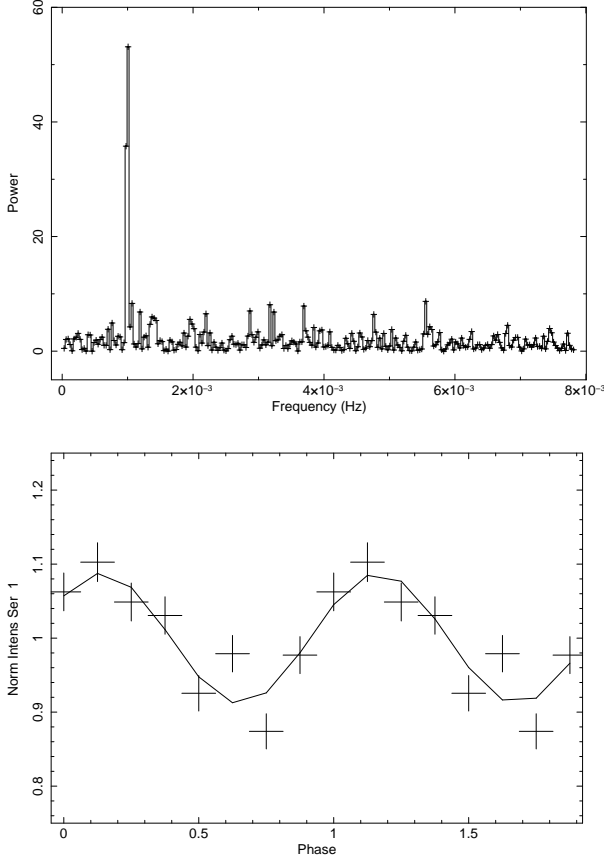


Figure 2. The power spectrum and e-folding phase diagram using ACIS 0.3–5 keV data

burst was detected at the time 51597 MJD - 15:29:55s (see par. 5 for details). The same procedure used for *Chandra* data was applied to 10s bin MECS/*BeppoSAX* light curve in the 3–5 keV energy band, with exclusion of the burst data. The best-fit period is (1013 ± 14) s with uncertainties at 1σ confidence level. Using this period value, we folded the light curves and a sinusoidal shape of the modulation was found (see figure 3) with a pulsed fraction of $\sim 4\%$.

We have also searched for periodicity in the *XMM-Newton* and *INTEGRAL* X-ray light curves, but no timing modulations have been detected.

5 BURSTS BEHAVIOR

In the soft X-ray band, this source was observed twice with *Chandra*, once with *XMM-Newton* and once with *BeppoSAX*; two thermonuclear X-ray bursts have been detected, during the *Chandra* and *BeppoSAX* observations. The first HRC/*Chandra* burst event was described by Homer et al. (2001). For the second not yet reported in the literature, we extract the MECS/*BeppoSAX* light curve in the 1.5–10 keV energy band and we detected an X-ray bursts starting at 51597 MJD (15:29:55 s), with a decay time of $\tau \sim 22$ s, computed from exponential fits to the burst decay profile. Fitting the spectrum (extracted at the burst peak with exposure time of ~ 10 s) with a simple blackbody model, a thermal temperature of 1.6 ± 0.1 keV with a extrapolated flux of $3.3 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$ in 0.1–30 keV energy band has been derived.

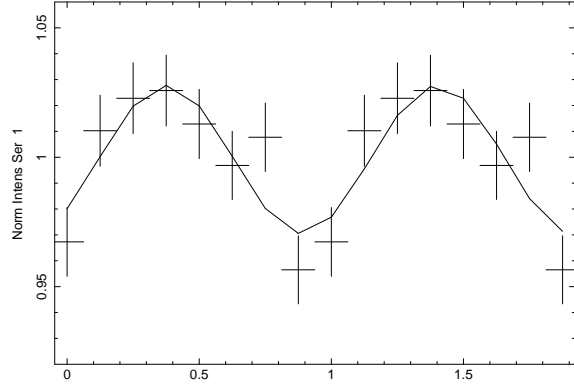


Figure 3. The e-folding phase using MECS 3–5 keV data

Galloway et al. (2008) have assembled all thermonuclear type-I X-ray bursts from the accreting neutron stars observed by *Ross X-ray Timing Explorer*, spanning on more than ten years period. They report only 7 X-ray bursts for 4U 0513–40 and place this source in the group of the bursters with infrequent short bursts at low accretion rate. The sources of this sample have long orbital period (longer than 80 min) and their behavior is explained by accreting of mixed H/He. The steady H-burning will then reduce or exhaust the accreted H prior of the burst ignition. This may not be the case for 4U 0513–40 which has a period of 17 min. This anomaly combined with the detection of two bursts in the soft X-ray observation may indicate that the bursts could be very frequent and weak for this source.

6 SPECTRAL BEHAVIOR OF THE PERSISTENT EMISSION

We extracted the *BeppoSAX* spectra before the burst event with the LECS, MECS and PDS exposure times of 1.6, 3.4 and 1.5 ks, and after the burst event with the LECS, MECS and PDS exposure times of 30.1, 67.5 and 31.2 ks, respectively.

IBIS and JEM-X spectra are produced summing up spectra of the source from each science windows in the period for which both instrument data are available. The exposure times are 103 ks and 36 ks for IBIS and JEM-X, respectively. For *Chandra* and *XMM-Newton* observations, to extract the spectra we use the total exposure time, 18.8 and 23.5 ks, respectively.

Each spectrum was fitted with a model of thermal Comptonization, in XSPEC by *COMPTT* (Titarchuk 1994; a spherical geometry was assumed), absorbed by a column density, N_H . Adding a blackbody component (modeled in XSPEC by *BBODYRAD* model) resulted in a substantial fit improvement for *Chandra* and *BeppoSAX* (after the burst) data. This reduces $\chi^2/\text{d.o.f.}$ from 452/310 to 374/308 for the *Chandra* data and from 173/130 to 155/128 for the *BeppoSAX* data, with the low corresponding F-test chance probabilities of 9×10^{-4} and 4×10^{-13} , respectively.

The spectral fit results are reported in Table 2 and spectra are shown in Figure 4 in different colors.

Table 2. Spectral analysis results. A N_H fixed to the Galactic column density was included in the fit. Error are given at 90% confidence level for one parameter of interest ($\Delta\chi^2 = 2.71$). The absorbed 1–10 keV flux are reported in units of 10^{-11} erg cm $^{-2}$ s $^{-1}$.

	kT_{BB} keV	T_0 keV	kT_e keV	τ	n_{BB2}	n_{COMPTT} 10^{-3}	Flux 10^{-11} erg cm $^{-2}$ s $^{-1}$	$\chi^2/\text{d.o.f}$
BeppoSAX spectrum before the burst event	...	0.22 ± 0.04	7^{+41}_{-3}	$3.6^{+2.6}_{-3.3}$...	$8.6^{+15.3}_{-8.5}$	15.2	156/127
BeppoSAX spectrum after the burst event	0.49 ± 0.04	0.18 ± 0.02	2.6 ± 0.2	6.8 ± 0.6	21 ± 16	38 ± 4	18.9	155/128
<i>XMM-Newton</i> average spectrum	...	0.068 ± 0.002	15^{+2}_{-10}	2^{+9}_{-1}	...	86 ± 20	8.9	573/387
<i>Chandra</i> average phase spectrum	0.34 ± 0.04	0.13 ± 0.05	5^{+24}_{-2}	6 ± 2	$3.9^{+2.7}_{-2.5}$	0.7 ± 0.4	0.7	280/284
<i>INTEGRAL</i> average spectrum	...	< 1.1	21^{+32}_{-16}	< 2.4	...	< 50	11.0	3/7

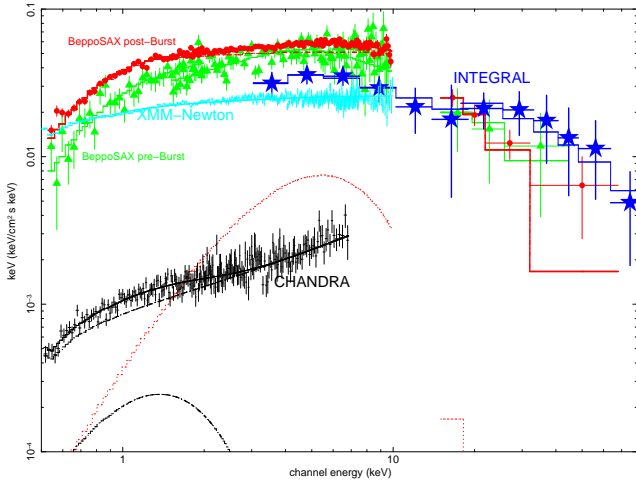


Figure 4. The *BeppoSAX*, *Chandra*, *XMM-Newton* and *INTEGRAL* spectra, shown together with the total model and its components.

7 DISCUSSION

In the present paper, we have shown that the binary system 4U 0513-40 in NGC 1851 exhibits a clear periodic signal with $P \simeq 17$ min in soft X-ray. This signal is sinusoidal and has an amplitude from $\sim 4\%$ to $\sim 10\%$. It is observed only in two observations (*Chandra* and *BeppoSAX* after the burst) when the source is in a typical high/soft state: the energy spectrum is well described as the sum of a Comptonized plasma with a temperature of $kT_e \sim 2$ –5 keV and an optical depth of $\tau \sim 6$ and a blackbody component with a thermal temperature of ~ 0.3 –0.5 keV. This result is independent from the extrapolated luminosity of the system, which spans from 0.7 to 5.2×10^{36} erg s $^{-1}$ in the 0.5–50 keV energy band, for *Chandra* and *BeppoSAX* (after the burst), respectively. This periodicity is not seen when the source is in a low/hard state (*XMM-Newton* and *INTEGRAL* data) and data is well reproduced by a simple Comptonized model with a plasma temperature of $kT_e \sim 15$ –21 keV and an optical depth of $\tau \sim 2$, without any thermal component. According to our present understanding, the black-body component in the soft state could originate at both the neutron star surface or boundary layer and the surface of an optically-thick accretion disk. The Comptonization component in the hard state may arise from a corona above the disk and/or between the disk and the stellar surface and accretion probably assumes the form of a truncated outer accretion disk (Olive et al. 2003). The origin of these spectral

changes is not clear, the thermal temperature (~ 0.3 –0.5 keV) confirm that the accretion disk is ionized and should not be subject to the standard ionization instability (Done et al. 2007).

The far-ultraviolet photometry obtained with the *Hubble Space Telescope* has shown the same periodicity described here (Zurek et al. 2009). These timing properties seen in UV/optical observations and the eclipse observed in the X-ray band imply that the origin of this modulation is of orbital nature and the inclination angle is higher than 80° (Arons and King 1993). In fact, the orbital motion modulates the soft thermal emission coming from a small region around the neutron star but not the Comptonization component generated in a more extended corona above and/or around the neutron star.

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